Melt Infiltrated (MI) SiC/SiC Composites for Gas Turbines Applications

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Team

- **GE Global Research:** **Material Development, Sample Testing, Rig Testing, NDE, Design Support**
- **GE Power Systems:** **End User, Component Design, Engine Testing**
- **Power System Composites (PSC):** **Component Fabricator**
- **Utility Sites:** **Engine Testing of Shrouds and Combustor Liners**
- **Solar:** **Engine Testing of Small machine Combustor Liner**
- **ORNL:** **Material Characterization**
- **ANL:** **NDE**
- **DOE:** **Program Support**

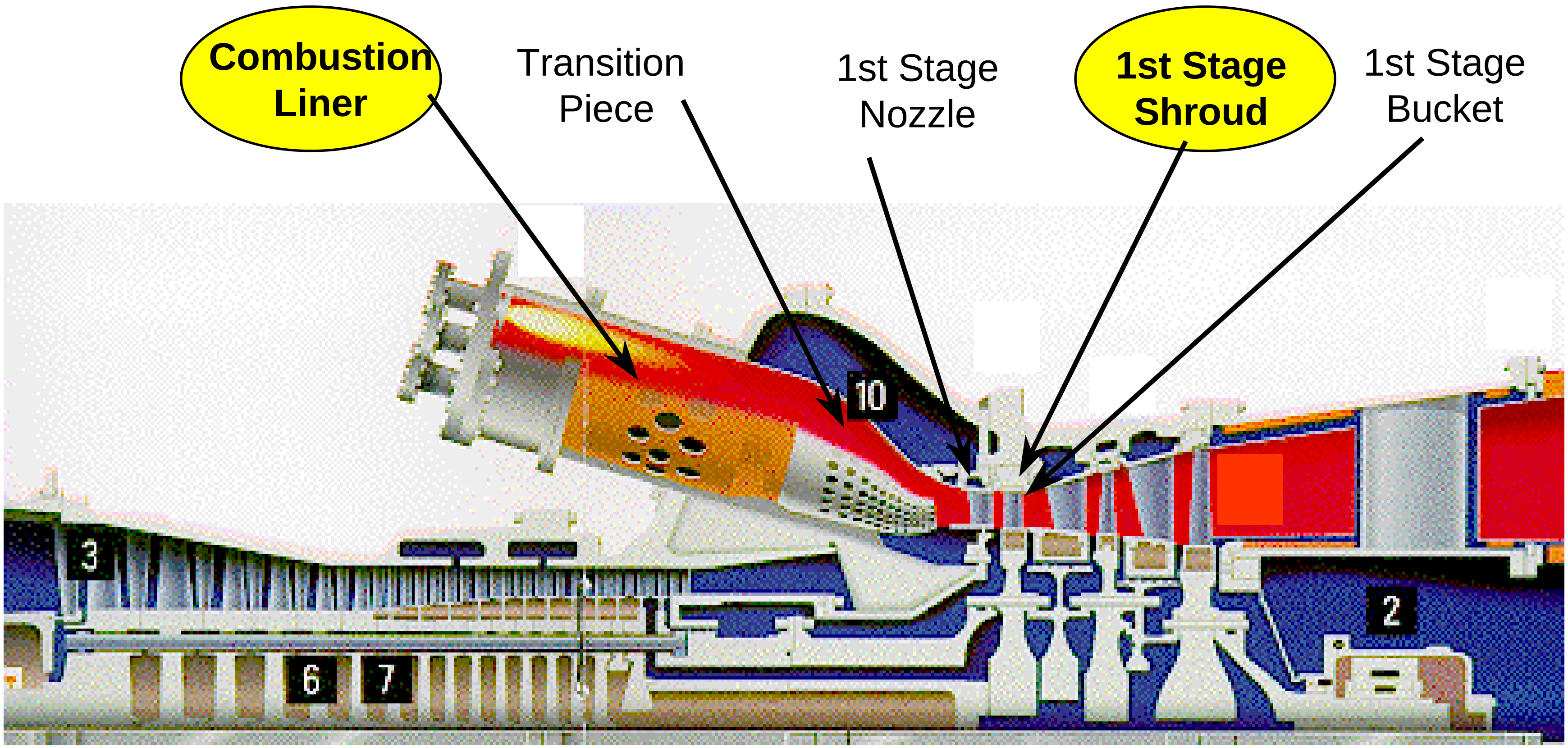
Wide Team involving Industrial Research Lab, National Labs, End Users, Utilities and Component Fabricator

Outline

- Team
- Applications & Payoff / Impact on DER Goals
- Material System
- Specific Goals / Objectives
- Tasks & Activities Status
- Technical Barriers and Project Risks
- Summary

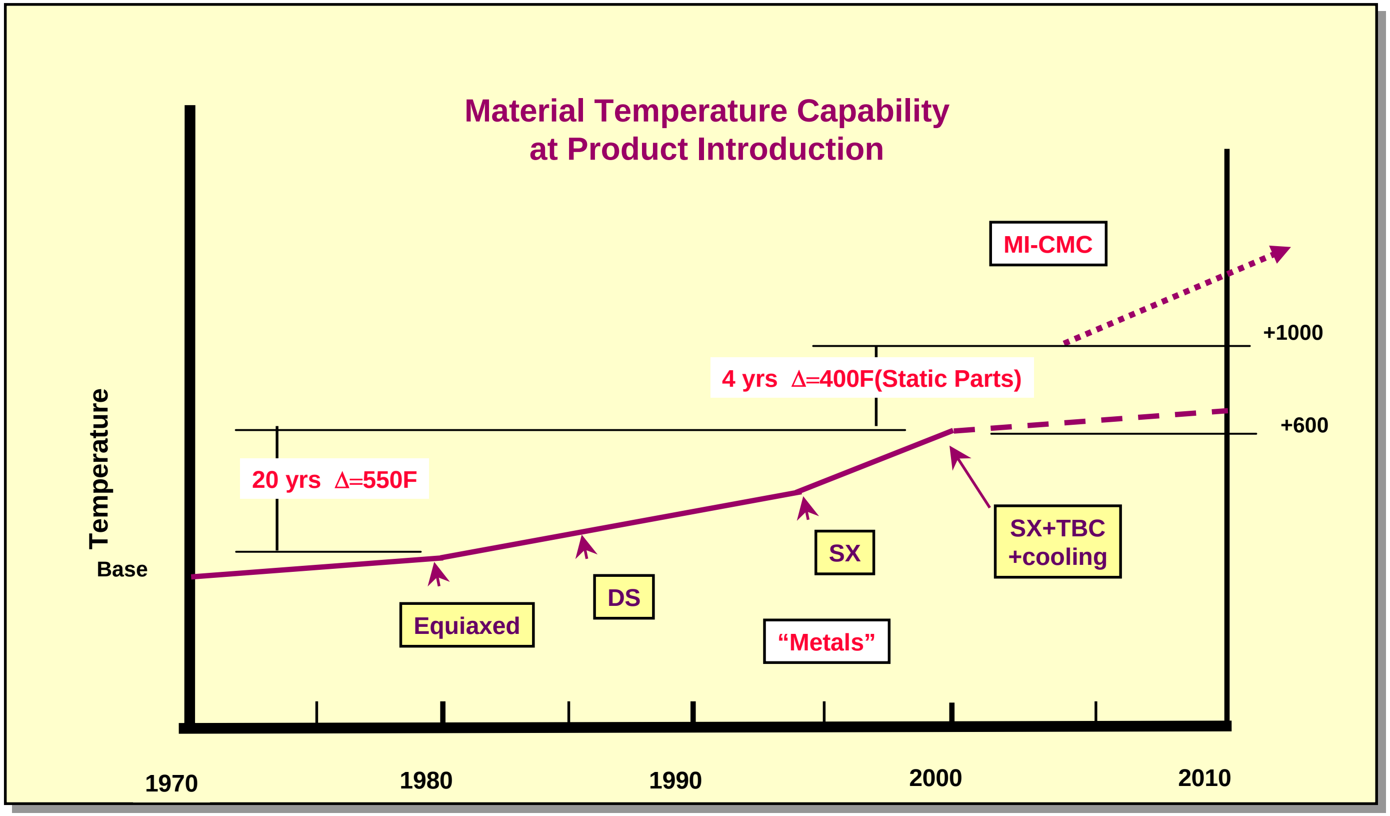
Goals / Objectives

Develop Melt Infiltrated Ceramic Matrix Composites (MI-CMCs) for Shrouds and Combustor Liners of Industrial Gas Turbines



- ***Stationary components represent the best short-term opportunity***

CMC Opportunity



- ***CMC's represent a game changing technology***
- ***DOE had the vision to start the CFCC program in early nineties***

Payoff & Selected Applications

- Higher temperature capability of CMCs allows reduction/elimination of air needed for cooling metallic components
  - Improvement in fuel efficiency
  - Reduction in harmful emissions
  - Higher output of machines
- Applicable to all classes of gas turbines
  - GE gas turbines range 45 KW to 280,000 KW
  - F-class & H-class machines most advanced
  - Installed base for F-class machines ~36 GW(US) & ~64 GW (worldwide) In 1999
- Initial focus on shrouds & combustor liners
  - Technology would flow to other stationary components, such as nozzles

Current Program focused on CMC applications in F-class machines

Payoff For Stationary Components

- Up to 1.1% point increase in simple cycle efficiency
- Increase in 3% output
- Market growth of 6%/year and 20% market penetration by 2020
  - US annual savings of ~290 Billion BTU of energy, equivalent to ~0.29 Billion cubic ft. of natural gas at a cost of ~$960 Million (2001 dollars)
  - Annual savings of ~4.3 Million MTCE of CO_2 emissions
  - Annual savings of ~51,000 MT of NO_x emissions
  - Extra power generation worth ~1.3 Billion dollars, further reducing the Cost of electricity to customers

Use of CMCs offers opportunity for enormous fuel savings, reduction in emissions and reduction in cost of electricity to customers

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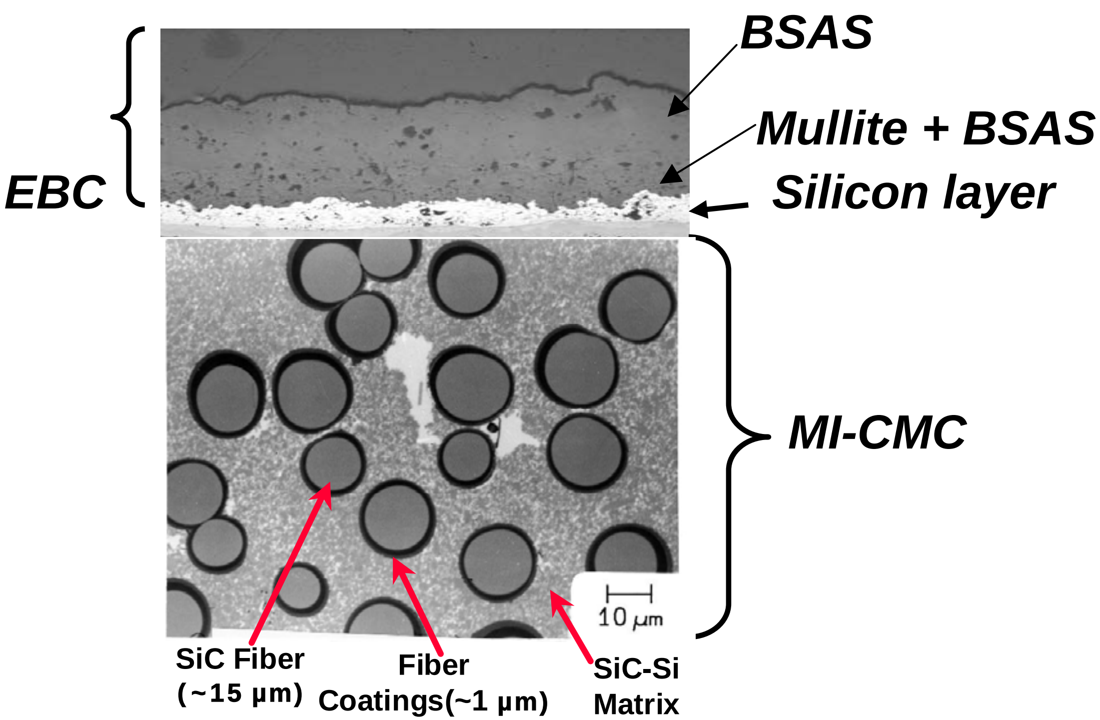
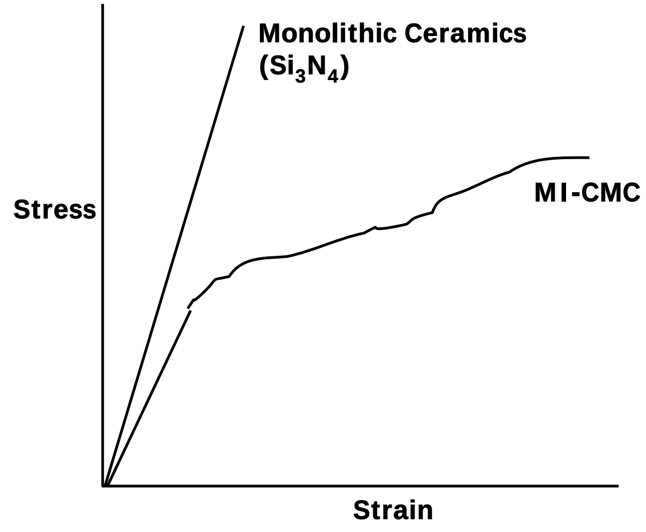
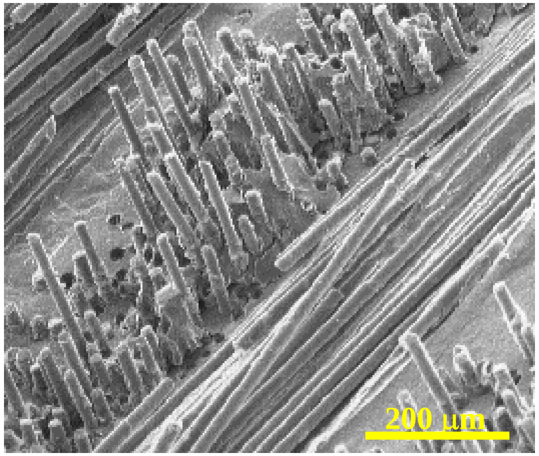
MI-CMCs





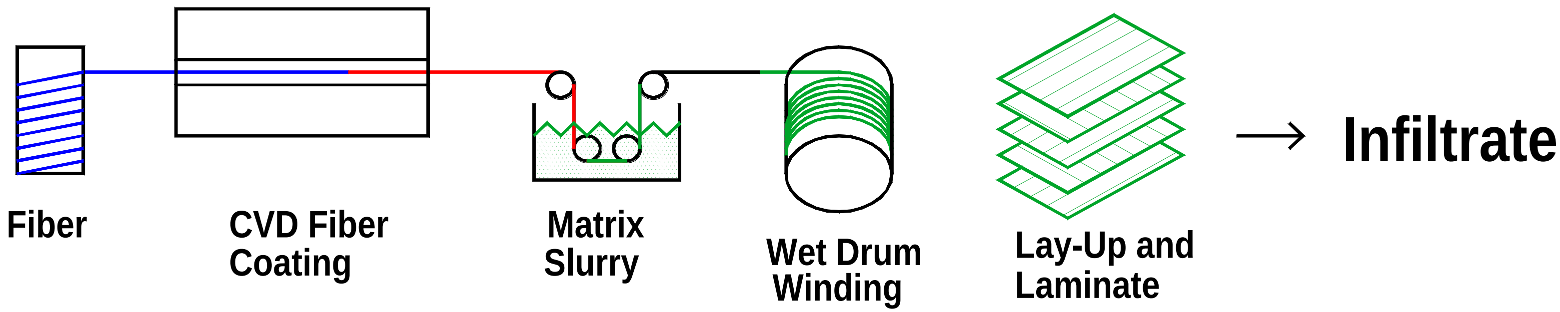
Fiber Reinforcement Increases Fracture Toughness (Damage Tolerance)



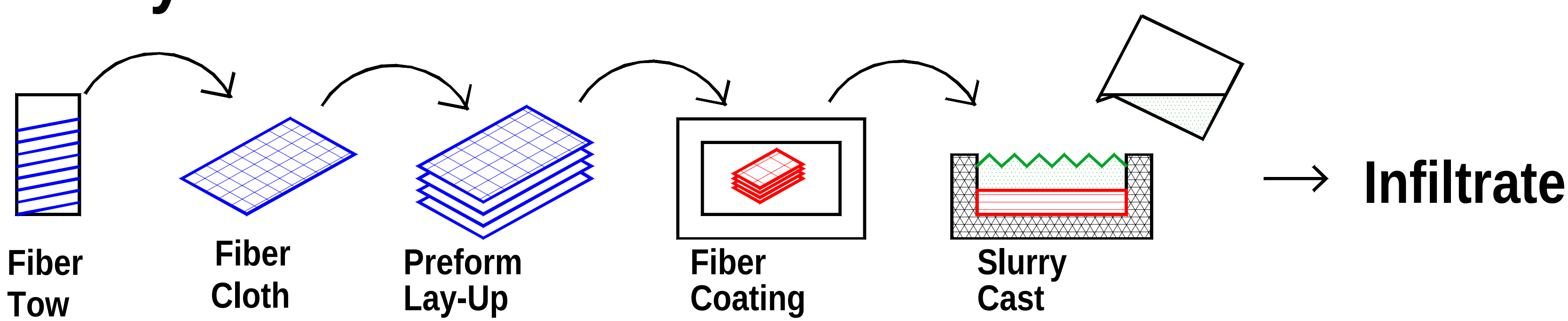
Fracture Surface

Melt Infiltration (M.I.) Composites

Prepreg MI

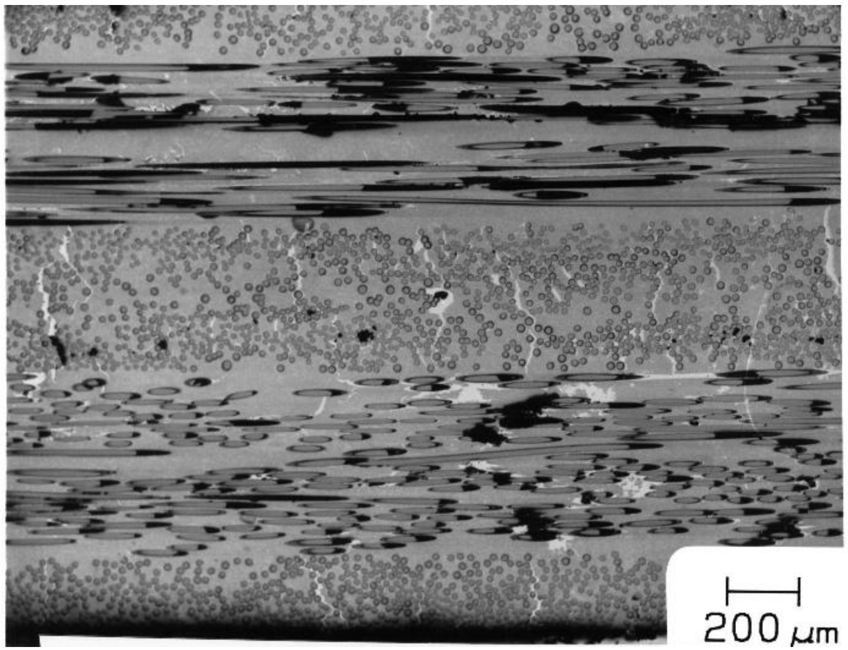


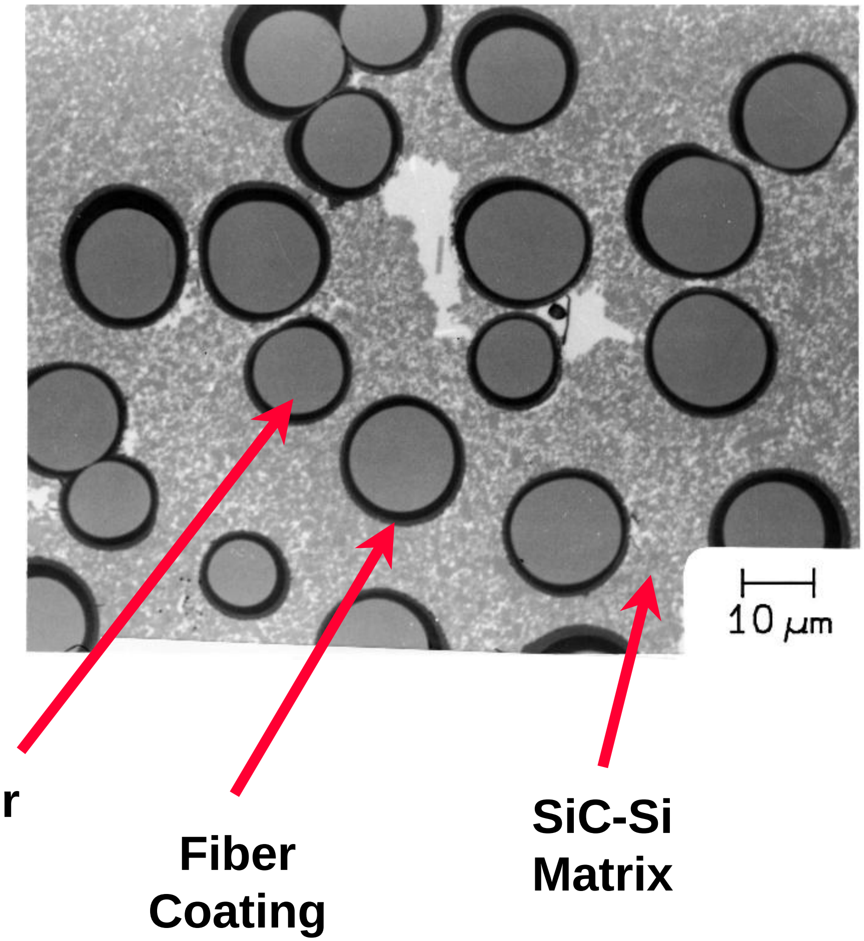
Slurry Cast MI



Work largely focused on Prepreg MI-CMCs

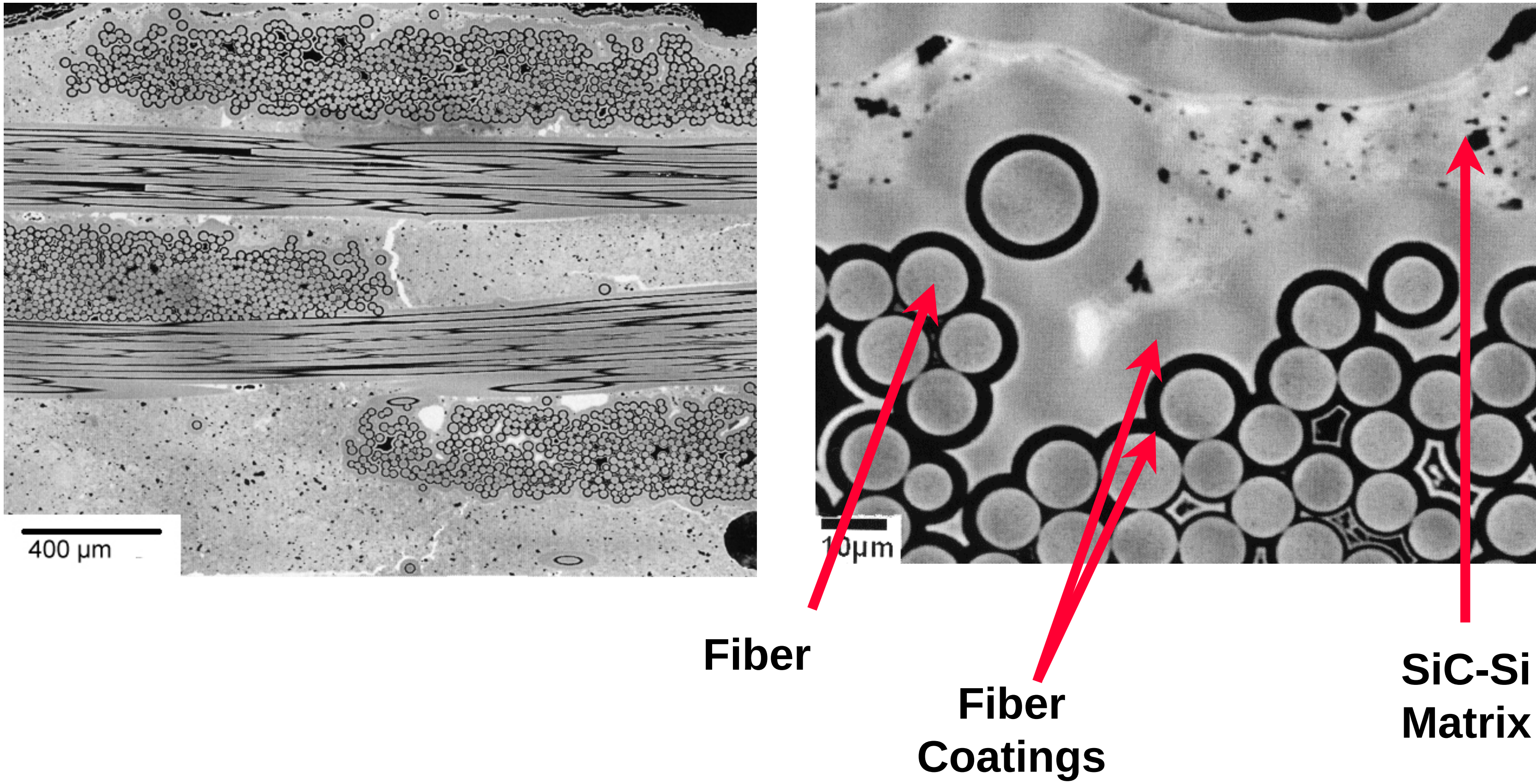
Microstructure of Prepreg MI Composites





Separated Fibers and Fiber Coatings; ~2-3% Porosity

Microstructure of Slurry Cast MI Composites



Fibers Bunched Together, Interconnected Fiber Coatings, and ~6% Porosity

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Specific Goals & Objectives

A. Conduct long-term testing of MI-CMCs in high pressure, high velocity gases (up to ~4000 hrs)

B. Design and field rainbow test unsealed First Stage Shrouds of F-class machines (~165 MW Simple Cycle and ~280 MW Combined Cycle) for over 4000 hrs

C. Design & field rainbow test combustor liners of F-class machines for over 4000 hrs

D. Design & field test sealed first stage shrouds of F-class machines for over 4000 hrs

E. Fabricate combustor liners for field test in a Centaur-50 Solar Machine

Focused on long-term testing to reduce life risk of components - still a high risk program

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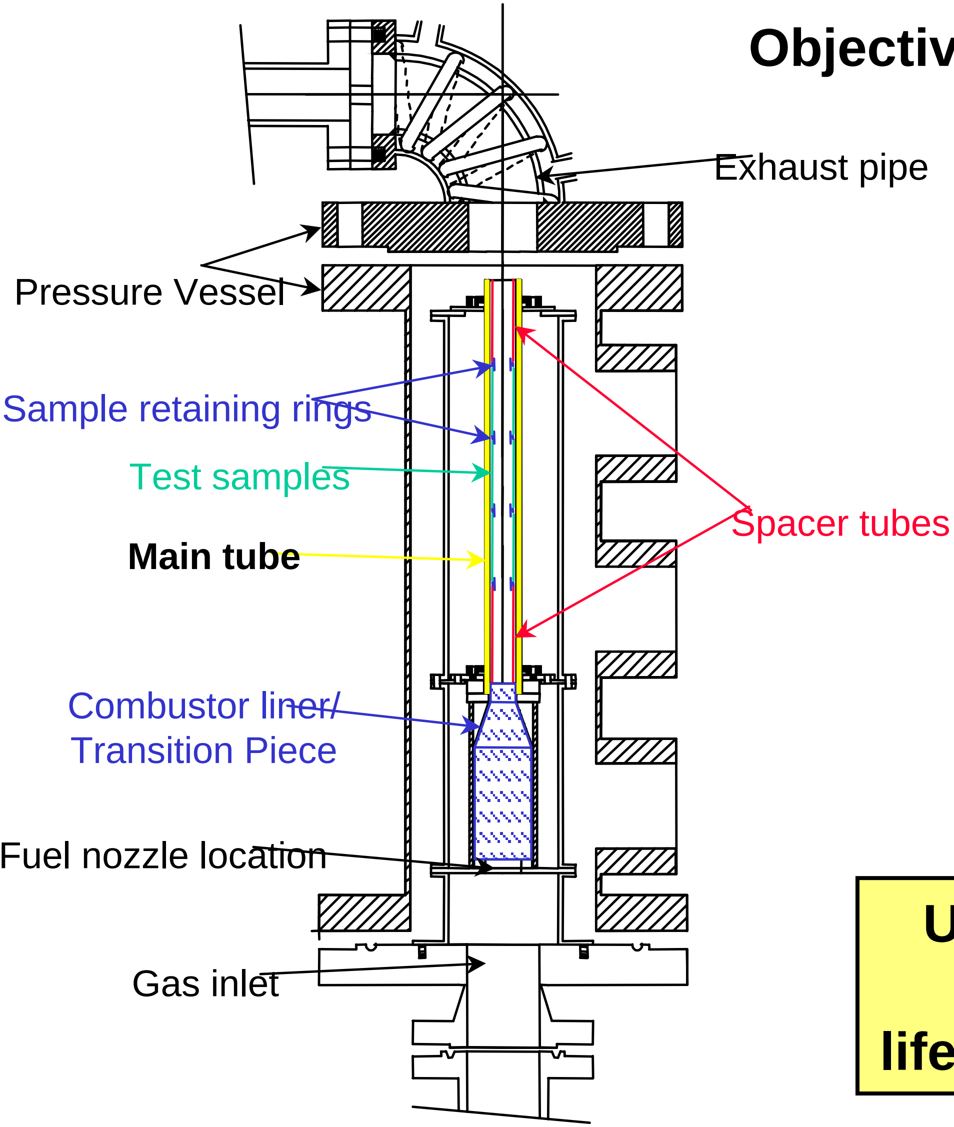
Task A: Long-Term Rig Testing



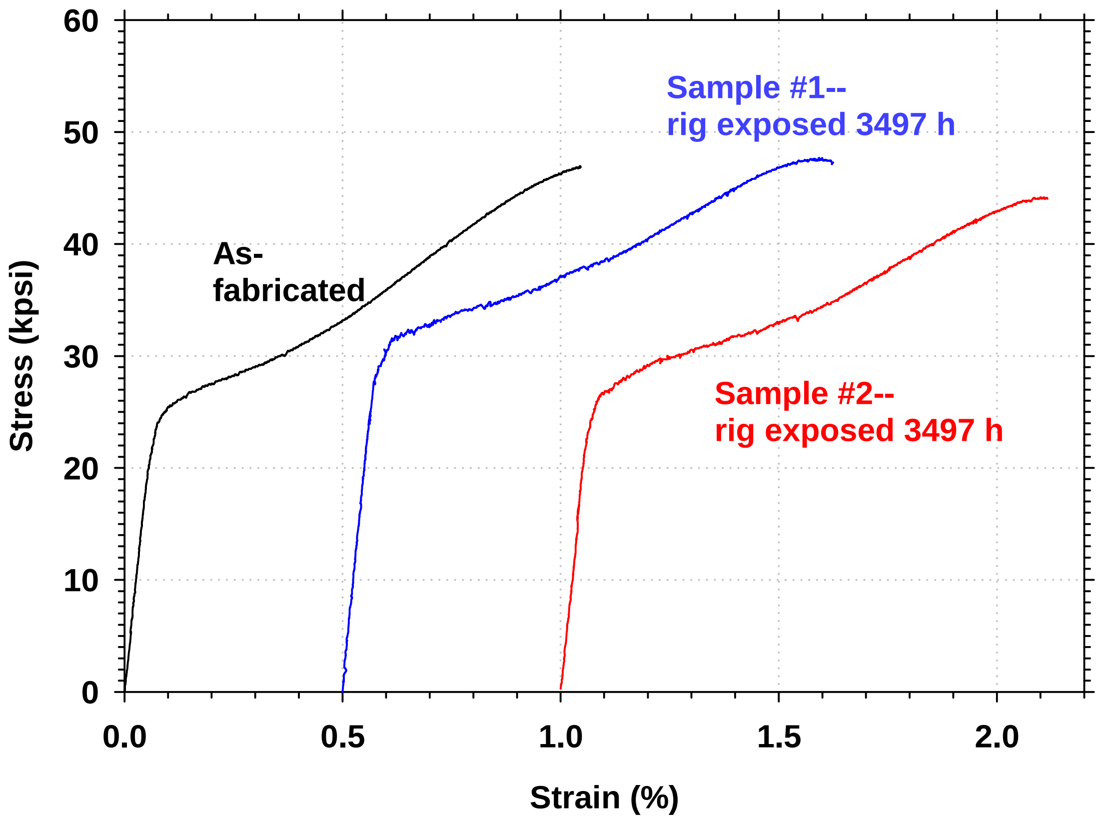
Objective: Evaluate the effects of long-term exposure in turbine conditions on surface recession and mechanical properties

T = 2050 F to 2200 F
P = 120 psia (8.2 atm)
Gas velocity = 410 fps (125 m/s)
xH_2O = 0.102
Fuel/air ratio = 0.030
Equivalence ratio = 0.52

Unique material testing facility being used for long-term life testing under turbine-like conditions

Task A: Long-Term Rig Testing

Residual 25 °C mechanical properties
of rig exposed EBC coated CMC samples



Remaining Tasks

- Characterization of Rig Tested Samples
- Additional testing up to ~500 hours

No degradation in mechanical properties of MI-CMCs for exposure up to ~3500 hours

Task B: Testing of unsealed 7FA First Stage Shrouds

Objective: Evaluate material performance of 7FA shrouds

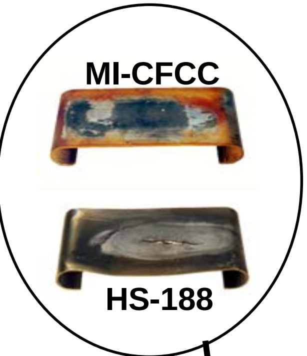
- Material Test
- Not an engine performance test
- No sealing to prevent cooling air leakage

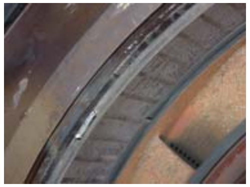
Sub-tasks:

– Design of Components, completed...	2001-2002
– Design Validation by 4 Rig tests...	2001-2002
– Fabrication of Components...	2001-2002
– Rainbow field test at a customer site	2002-2003
– Characterization of engine tested shrouds	Ongoing

First ever hot stage CMC component test at a large utility site

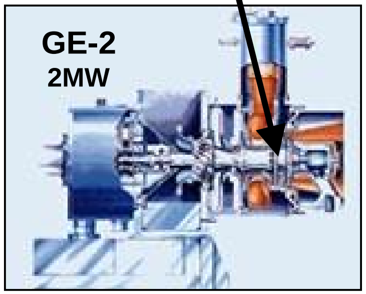
Development Path of CMC Shrouds

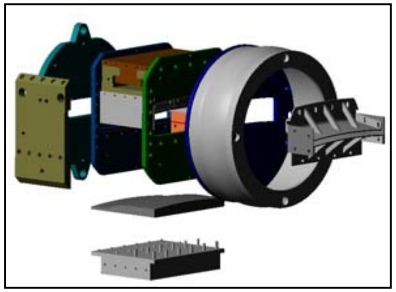




Stg. 1 Shroud

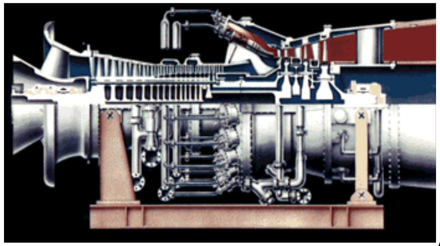
Stg. 2 Shroud

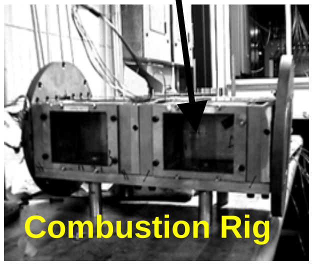




CMC Shroud Rig Test

7FA 160MW





Material Development and Testing 1992-2002

Feasibility Rig Tests 1998

200+ cycles & 200 hrs

Small Engine Testing 1999-2000

60 cycles & 1000+ hrs

Rig Qualification Unsealed Design 2001-2002

50+ cycles & 300 total hours

Field Engine Validation Test 2002-2003

14 cycles & 5366 hrs

Rig Qualification Sealed Design (2004)

Engine Field Test (2005)

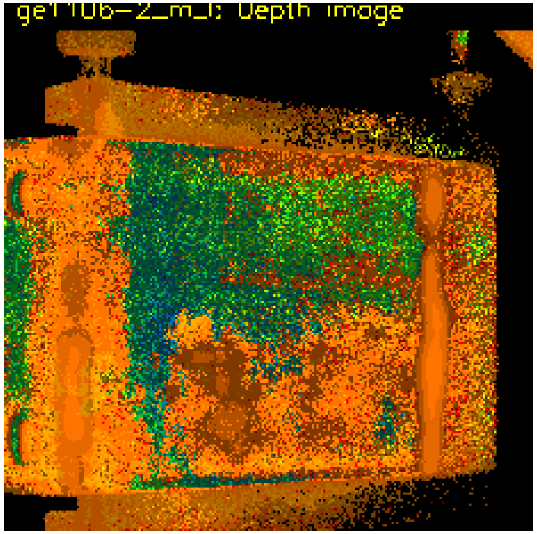
Completed

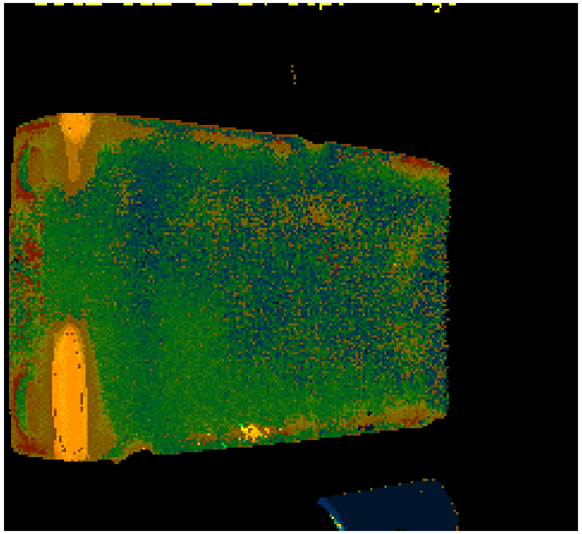
In Progress & Future

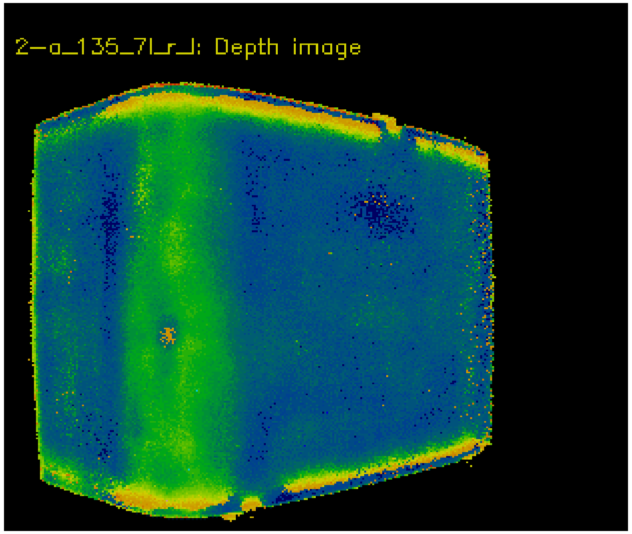
Progressive "stepping stone" approach reduces development risk

NDE of Shrouds

2001 **Engine Shrouds** **2003**

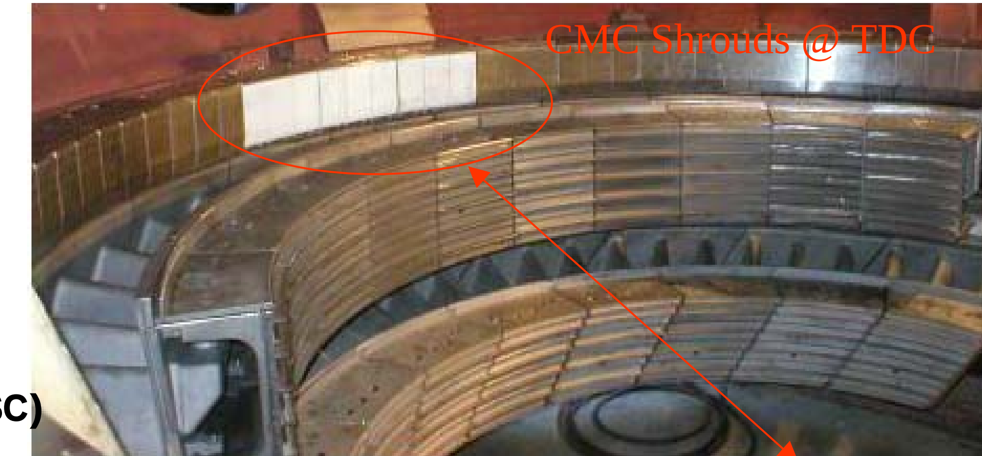






Tremendous Improvement in Quality of Shrouds

Rainbow Engine Testing of 7FA+ First Stage Shroud



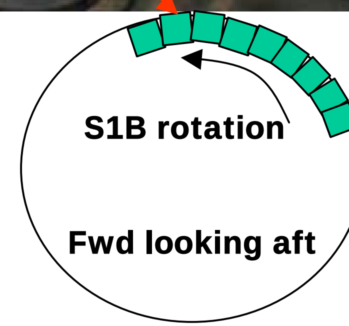
<u>Engine</u>

- GE 7FA+ in Combined Cycle
  160 MW (SC)
  265 MW (CC)

<u>Hardware</u>

- 9 CMC shrouds
  – 6 Prepreg (GRC); 3 Slurry Cast (PSC)

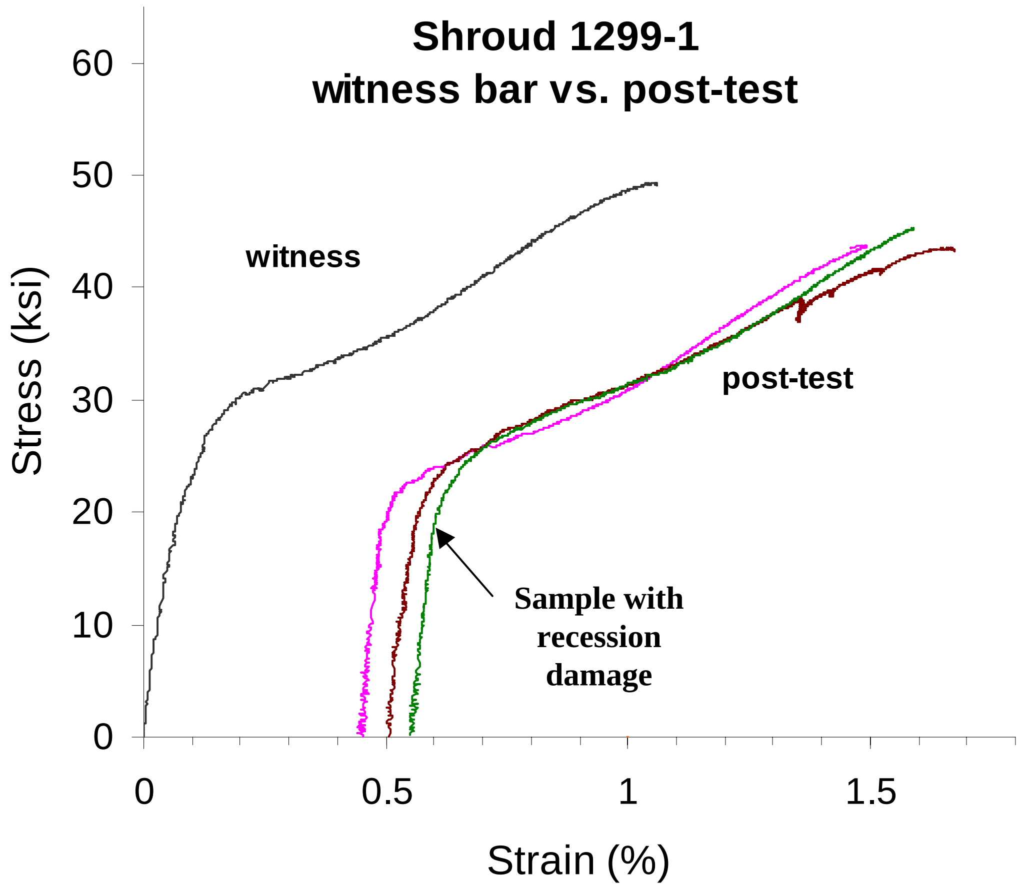
<u>Status</u>



- Completed over 5000 hours of engine testing
  - 14 starts
  - Parts being characterized
- Material temperature exceeding 2250 F (1230 C)
- No structural damage to CMCs
- EBC damage at several locations
  - Tooling bumps increase the EBC damage on slurry cast MI composites
  - Work being done to understand other EBC damage mechanisms

Successful Rainbow Testing of First Stage Shroud in a Large Gas Turbine

CMC Shroud Post-Test Characterization



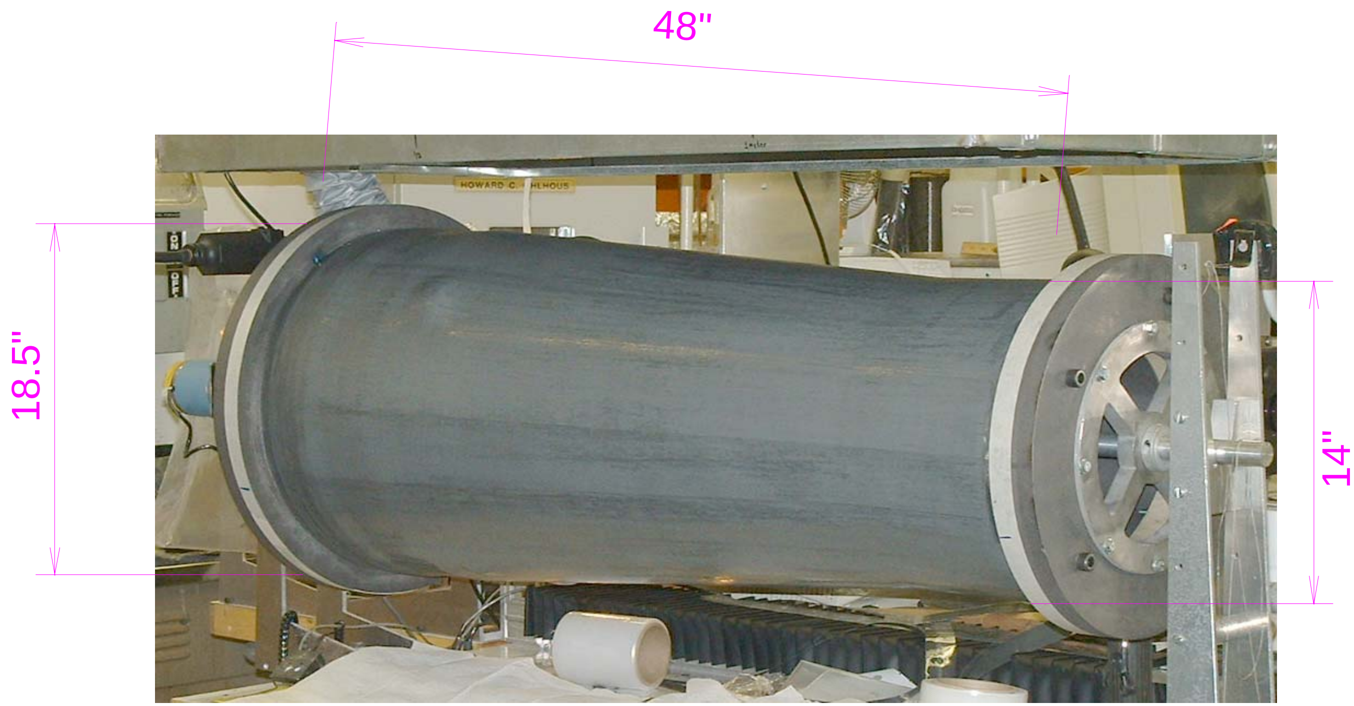
- **Characterization ongoing now**
- **Shroud with EBC damage (spall) characterized**
  - **Worst recession ~31 mils**

No degradation in mechanical properties

Task C. 7FA Liner

Objective: Design and Rainbow Field Test a 7FA liner

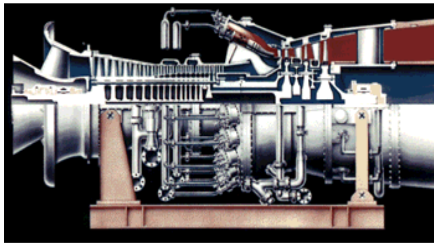
Sub-tasks:	Design of Components	2002-2003
	Fabrication development	Ongoing
	Rig Test for Design Validation	2004
	Rainbow Engine Test	2005

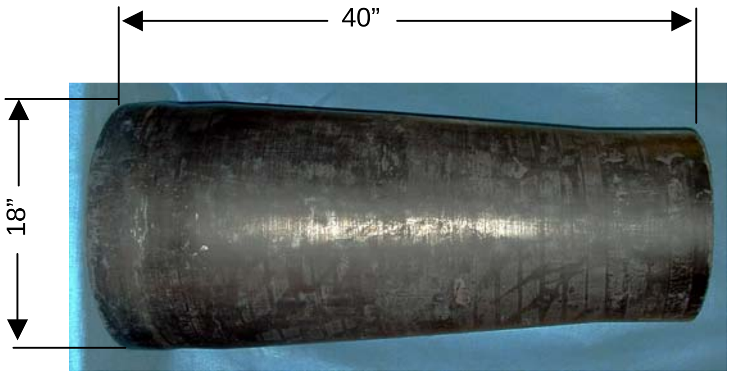


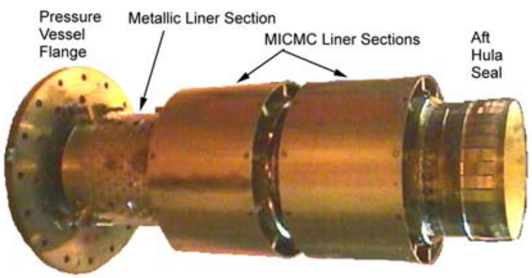
Three times the size of the largest CMC component ever made

Development Path of CMC Combustor Liners

7FA 160MW







Material Development and Testing 1992-2002

Feasibility Rig Tests 1999

200+ cycles & 150 hrs

Preliminary Design Rig Qualification Test (2004)

30 cycles & 50 hrs

Final Design Rig Qualification Test (2004)

30 cycles & 50 hrs

Field Engine Test (2005)

Completed

In Progress & Future

Lessons learned from shroud program allows simpler development path for combustor

7FA Combustor Liner

- First liner fabrication trial showed significant challenges
  Shape distortion, wrinkles & incomplete infiltration

• Size of 7FA Liner represents a big technical challenge – Factor of 6 bigger than anything made by us

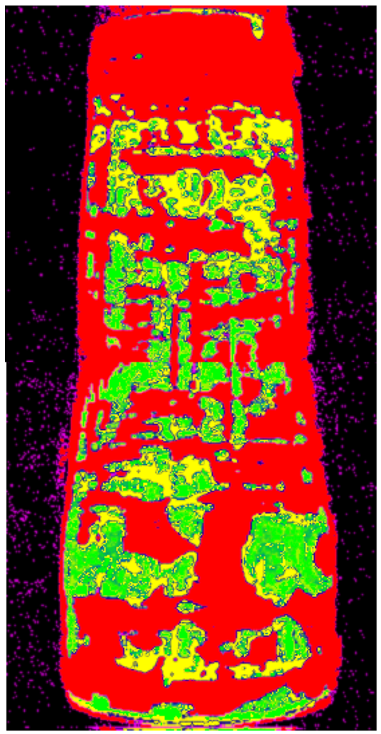
7FA Combustor Liner: Status

- **Design completed for rig test**
- **Rig test liner**
  - An order of magnitude better than trial liner
  - No shape distortion
  - No wrinkles
  - Almost complete infiltration
  - NDE shows defects
- **Rig Test scheduled for 2004**

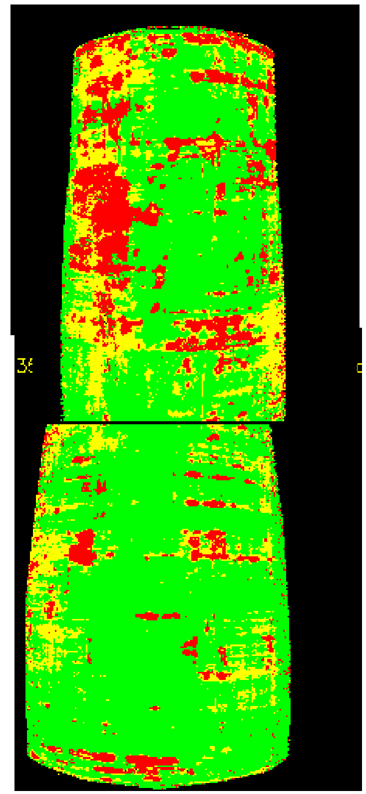
Liner on schedule for an Engine Test in 2005

7FA Combustor Liner: NDE

Trial Liner



1st Rig Liner



- Bad (delaminated)
- Poor (porosity)
- Good

Major improvement in 7FA liner quality

Task D: Testing of 7FA First Stage Shrouds with Sealing

Objective: Evaluate performance of 7FA shroud system
- Complete shroud system with in between sealing
- Up to ~48 shrouds

Sub-tasks:

– Component and Seal Design...	2003-2004
– Design Validation by Rig tests...	2004
– Fabrication of Components...	2004-2005
– Field test at a customer site	2005
– Characterization of engine tested shrouds	2006

System and Seal Design compatible with CMC shape capabilities and properties represents the largest challenge

Task E: Solar Combustor Liner

Objective: Fabrcate Prepreg MI-CMC liners for testing in a Centaur-50 Solar Gas turbine

Sub-tasks:

- Fabrication of Liners (Ongoing) 2003-2004
- Field testing by Solar 2004-2005
- Characterization of engine tested liners 2005

Fabrication & Testing of Solar Liner represents synergistic opportunities for Solar and GE

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Technical Barriers

- **Component Design (both for combustor liners & shrouds)**
  - **Expansion mismatch between metal & ceramic**
  - **Low stress capability of CMCs**

  ➢ **Require several iterations on design, design validation by several rig tests, followed by characterization**

- **Sealing of Shrouds**
  - **Needed to prevent air leaks**
  - **Seals operating at higher temperatures than with metallic components**

  ➢ **Require several iterations on design and design validation**

- **Fabrication of Defect-free CMC liners**

  ➢ **Scale up issues to be addressed based on prior experience**

- **Component Life**
  - **Required EBC lives are of the order of over ~24000 hrs**
  - **Required component lives are of the order of 48000+ hrs**

  ➢ **Gradual Improvements based on Field Tests**

EBC Life and Component Design/Sealing represent key challenges

Project Risks

- **Finding a Suitable Test site for 7FA machines**
  - **GE has the largest fleet of F-class machines in field**

  ➢ **Requires flexibility to coordinate with test site…. Could impact schedule**

- **Limited Opportunities for Borescope Examination**
  - **Loss of at least 160 MW of power**

  ➢ **Need to ensure safe operation in between inspection; use additional diagnostic instrumentation**

- **Consequences of CMC failure in a large machine are tremendous**
  - **Loss of at least 160 MW of power**

  ➢ **Need to take extra rig testing steps to ensure the system safety**

Machine size represents opportunities as well as challenges

Summary

- CMCs represent a game changing technology for industrial gas turbines (400^{o} F improvement over metals)
- CMCs offer opportunities for enormous fuel savings, reduction in emissions, and reduction in cost of electricity to customers
- Unique high pressure, high velocity rig being used for long-term testing of CMC samples
- Over 5000 hours of successful field rainbow testing of 7FA shrouds performed
- Design and Fabrication of 7FA liner (~48” long x ~16” in dia) ongoing now
- Future work focused on design, fabrication & engine testing of sealed shrouds, fabrication of CMC liner for a Solar test, and design, fabrication & rainbow testing of 7FA liner

GE working with DOE in a risk-reducing, step-wise approach for developing CMCs for Industrial Gas Turbines